Reliable Free-Space Optical Communication System Performance for Matching Multi-level Customer Needs: Using Hybrid Modulation System with Deep Reinforcement Learning

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***Abstract*—In the recent decades, free-space optical (FSO) communication technology has gained significant importance owing to its promising unique features: high user capacity, license-free spectrum, ease and quick deploy-ability. However, the performance of FSO communication systems depends on the uncontrollable terrestrial atmospheric effects. The second main challenge is that the FSO system performance degrades as a line-of-Sight (LoS) technology due to the misalignment transmitter and receiver. The third challenge is the consideration of time value of money, which is central to most engineering economic analyses in employing communication systems. The opportunity cost of making one choice over another must also be considered. This paper presents a proposed FSO system design model for mitigating the three performance challenges we mentioned. The results show an enhancement by 83.34% in system efficiency in case of moderate scintillation (using gamma-gamma model). This proposed hybrid model is proved to be applicable to any atmospheric channel conditions.**

***Index Terms*—Free-space optical communication (FSO), atmospheric turbulence, deep learning (DL), wavelength division multiplexing (WDM), pointing error, multiple-input-single-output (MISO), single-input-multiple-output (SIMO), multiple-input-multiple-output (MIMO), bit-error-rate (BER), signal-to-noise ratio (SNR), equipment mean life-span.**

I. Introduction

Free-space optical (FSO) communications is a technique of communication engineering that involves using an optical source, whether laser or light-emitting diodes (LED), to carry and transmit information through an unguided medium, such as terrestrial atmosphere, water, or space to a receiver. Short-range FSO links are commonly used as an alternative to RF links for the last or first mile to provide broadband access networks to homes and a high bridge between the local and wide area networks [1]. In 2008, the first 10 Gbps FSO systems were commercially introduced, making it the highest-speed commercially available wireless technology at the time. Research and industry continue to increase the capacity through integrated FSO/Fiber and FSO/RF communication systems and wavelength division multiplexed (WDM) FSO systems [2]. Terrestrial FSO has proven to be a significant complementary technology in addressing the contemporary communication challenges, especially bandwidth/high capacity requirements to end users with a reliable cost. However, the dominant challenge for FSO systems' performance is the uncontrollable atmospheric conditions that the unguided traversing optical signal suffers. The power of the optical signal degrades due to meteorological events such as high temperature, rain, snow, humidity, fog, and sandstorm. In addition to meteorological effects, the system performance is dependent on the alignment between the transmitter and the receiver [3].

The first challenge appears in the uncontrollable behavior of the atmospheric channel. Dense fog and sandstorms can cause FSO link drop due to the severe scattering and divergence of the traversing optical beam. Due to the existence of some companies (including petrochemical industries) and cities that are still under construction in these areas (like Borg Al-Arab and Alamein in Alexandria City, Egypt) in desertous regions in Egypt and the endless need for high capacity reliable communication generated the need to search for communication technologies that can achieve these needs with affordable cost [4]. Since those rural areas, for high cost, are poorly supported with radio-frequency systems (RF) and fiber communication services, FSO is an attractive, affordable technology that fulfills the need of these companies for high capacity. In the case of the cities under construction, FSO is recommended to be an effective temporary intra-communication method till RF base stations are planned and built for these rural areas. In addition to optical signal attenuation, the optical beam encounters the effect of atmospheric turbulence. Atmospheric turbulence is dependent on the meteorological elements atmospheric pressure, wind speed, and the index variation of refraction due to temperature non-homogeneity. This causes the deviation on the propagation optical radiation resulting in received chirping optical pulses. Atmospheric turbulence causes random fluctuation of the atmospheric refractive index leading to the change of the phase of the propagating opti-

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cal beam. The random temperature change is a function of temperature, atmospheric pressure, height from sea-level, and wind speed [5].

The second challenge that degrades the FSO systems' performance is the effect of pointing errors. Since FSO is a line-of-sight (LOS) technology, its performance depends on the alignment between the transmitter and the receiver. A pointing loss results due to the misalignment between the transmitter and the receiver. This misalignment happens due to building sway or strong wind [3]. The ideal case is that the received beam falls precisely at the origin point of the receiver lens, which never happens in practical implementations except when used in the back-to-back configuration in which the transmitter is stuck to the receiver with zero link distance. The pointing error in free-space optical (FSO) communication has two types with respect to 1) The area of the receiver aperture, which is commonly circular lens, and 2) The origin (center) point of the receiver lens. The two types of pointing errors are: 1) Linear misalignment, which occurs when the received beam is displaced from the receiver lens origin by a distance on either x or y-axis concerning the origin. Mathematicians use this case in modeling pointing errors for approximating the actual complicated case of pointing errors. However, in practice, it rarely takes place, and 2) Radial misalignment is the general error that is commonly experienced by which the received beam is displaced from the origin by an amplitude and angle. The pointing error is mainly dependent on the receiver aperture diameter and link distance. In practical implementations, radial misalignment is more common than linear misalignment [4].

The third challenge considers the scale of the engineering economy and the average lifespan of optical devices. The unplanned use of optical devices leads to diminishing the lifespan of used optical devices. Therefore, engineers seek in their mitigation designs to achieve the system's high performance and reliable cost [6].

This paper proposes a model for the mitigation of the FSO communication system challenges. The main objective is to enhance the user data rate, increasing coverage range, achieve the least BER, reduce the power consumption for data transmission. The proposed system is expected to cover multi-level customer needs with the least resulting tradeoffs. Deep Reinforcement learning is used to help the system select the appropriate devices according to the type and priority of data requested to be sent: achieving the least BER in a short time, allowing the customer to select the best choice with the least performance tradeoffs. To the best of the authors knowledge, the implementation of deep learning in this area of FSO communications systems has not been investigated yet, which emphasizes the contribution of this work. The system performance is studied both simulation using an integration between MatLab 2020 and OptiSystem 17.0. Very-High-Device- language (VHDL) programming is considered for implementing the system practically.

The paper is organized as follows: After the introduction in Section 1, the process of our proposed system is explained in Section 2. The performance evaluation of the proposed system is presented in Section 3. Section 4 presents and discusses the results showing the efficiency of the proposed models compared to familiar modes in the literature. Finally, Section 5 is devoted to the conclusions.

II. Process of the Proposed System

The explanation of our model is covered through three main parts: the block diagram of the proposed system, the flow chart of the processing of the proposed system, and our used algorithm of deep reinforcement learning tool.

A. Block Diagram of the Proposed System

The block diagram of the proposed system is shown in Figure 1. The system requires from the user two inputs:

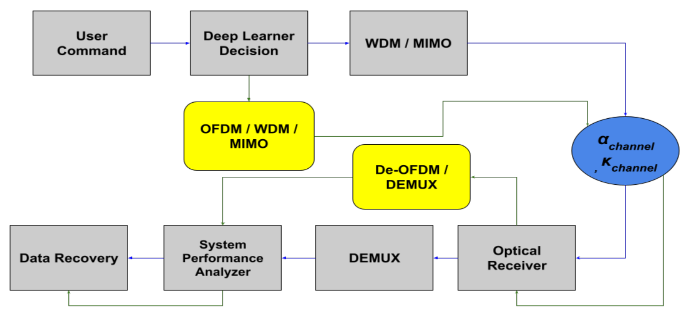

Fig. 1. The proposed mitigation model. The blue path denotes the path of the first model using WDM/MIMO. The green path denotes the path of the second model using OFDM/WDM/MIMO. $\alpha_{channel}$ and $\kappa_{channel}$ denote attenuation factor and scintillation index, respectively, due to the atmospheric channel climate conditions

the message, which can be an image, audio file, compressed file, video-stream, etc; and its priority, which can be high (urgent and important to be sent) or low (can tolerate some delay). The message and its level of priority are input as parameters for the deep reinforcement learning tool. According to the type of data, its priority and channel conditions, the deep learner chooses one of two paths to transmit the message through it. The blue path in Figure 1 is designed for the mitigation of the three stated challenges in case of the dominating effect of attenuation due to the channel. The green path is recommended for mitigating the effect of power scintillation using a hybrid system using a combination of orthogonal-frequency-division-multiplexing with wavelength-division-multiplexing for a multiple-input-multiple-output system (OFDM/WDM/MIMO technique). The system interchange between the two paths is based on the requirements input by the user, including the required data rate, current power budget, and the priority of the data required to be sent. For the blue path, the message is converted from electrical to optical signal and distributed using WDM. If multi-users are transmitting data with high priority at the same time, the system can activate the MIMO, multi-input-single-output (MISO), configuration for data transmission. The input parameters for the deep learner tool, as will be explained in a later subsection, selects the appropriate receiving devices, multi-output or single-output, according to the system and channel status. Then, the message is sent to traverse the atmospheric channel. The optical signal suffers attenuation and power scintillation due to atmospheric turbulence. The overall channel attenuation factor is symbolized by $\alpha_{channel}$. This results due to the interaction between the transmitted photons and terrestrial atmospheric molecules, including air molecules and aerosols, results in a power loss mechanism modeled by Beer-Lambert law. The Beer-Lambert law describes the transmittance of an optical field through the atmosphere as a function of transmitted wavelength and propagation distance. In addition, the optical beam angle divergence increases due to the scattering of photons with the molecules and aerosols, resulting in a larger received beam size than the receiver aperture. Besides the power loss and scattering effects, pointing error at the receiver dramatically affects the amount of power received if it is not considered [4], [5]. The Beer-Lambert law is given by [5]

$$\tau(\lambda, L) = \tau_s + \tau_\alpha = \frac{P_R}{P_T} = \exp\left(-\gamma_T(\lambda)L\right), \quad (1)$$

where $\tau(\lambda, L)$ is the transmittance of the atmosphere at operating wavelength λ and link range L, $\gamma_T(\lambda)$ is the total attenuation in dB/km. τ_s and τ_α are the transmittance due to scattering and absorbing effects, respectively. P_R and P_T are the received optical power and the transmitted power, respectively.

The second effect that the optical signal suffers from is atmospheric turbulence, which is expressed by scintillation index $\kappa_{channel}$. Atmospheric turbulence is dependent on the meteorological elements atmospheric pressure, wind speed, and the index variation of refraction due to temperature non-homogeneity. This causes the deviation on the propagation optical radiation resulting in received chirping optical pulses. The study in this thesis considers only studying the system performance degradation due to optical beam attenuation by absorption and scattering. Atmospheric turbulence causes random fluctuation of the atmospheric refractive index leading to the change of the phase of the propagating optical beam [5]. The random temperature change is a function of temperature, atmospheric pressure, height from sea level, and wind speed. The literature shows many contributions to model the turbulent channel. The most commonly used model is the gamma-gamma model. The gamma-gamma irradiance model is given by [5]

$$f_I(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}), \quad (2)$$

where $K_a(.)$ is the modified Bessel function of the second kind of order a, α is a positive parameter representing the effective number of large-scale eddies of the scattering process, which is larger than that of the first Fresnel zone, β represents the effective number of small-scale eddies which are smaller than the Fresnel zone or the coherence radius, I is the irradiance of the field, and $\Gamma(.)$ is the gamma function. The irradiance of the field is expressed as [5]:

$$I = I_0 \exp(2\chi), \quad (3)$$

where I_0 is the level of irradiance fluctuation in the absence of air turbulence and χ is the first-order log-amplitude of the field.

After the channel, the signal is collimated by a 15 cm diameter lens. The reason for choosing this diameter is the conclusions deduced by the authors in [4]; which is when increasing the receiver aperture diameter more than 20 cm, the performance of the receiver module is degraded due to the effect of the ambient noise. The increase of the ratio between the useful signal to the ambient noise is inverse proportional to the diameter of the receiver aperture. The collimated beam is received by an optical receiver module in which the optical signal is converted back to an electrical signal which is then de-multiplexed, Then, the de-multiplexed signal passes through system performance analyzer tester. In this stage the resulting system performance parameters are measured and recorded in the system memory to be used later in the optimization stage. More explanation for the optimization stage is covered in the next two subsections. After testing the performance of the signal, the message is recovered at the end-user node.

For the green path, the electric signal passes through an extra step before being converted to an optical signal; which is OFDM modulation. At the receiver, the received signal is converted from optical to electrical signal, de-multiplexed and then demodulated. In [4], the authors proved that OFDM modulation enhanced the performance of the received signal. They expected from their work that the use of OFDM is efficient for mitigating the effect of atmospheric turbulence.

B. Flowchart of Proposed System Processing

The flowchart presenting the process of the proposed system is shown in Figure 2. The system starts by the user input for the message and its level of priority. The user inputs, and other parameters including the parameters of real-time channel status are collected in a matrix and input to a comparator. The comparator compares between the input matrix with the matrices saved in history. If the input matrix matches one of the previously saved, or learned, matrix; the signal will be directed directly to the hardware phase. If the input matrix is not matching any of the stored matrices, the matrix is directed as an input for the real-time deep reinforcement learner tool which outputs its decision in a form of a matrix. The user input data and the output-learned matrix are saved in the system storage unit for further use. After the learning and decision phase, the message passes through the hardware phase. The system checks the en-ability of the devices that are required to be used for the message transmission and reception. Then the matrix is input to a decision comparator: whether the transmission requires the default enabling of devices or requires selected parameters for some devices. If the matrix does require the default enabled devices, an enabling trigger is sent to the hardware and then the message is sent over the channel. If the transmission requires certain selected parameters for the devices, the parameters are changed and then the trigger is sent for the hardware, and the message is sent. After the message traverses the channel, the message is received and the system, by comparing between the sent and the received message, measures the status of the performance parameters of the signal (power received, SNR, BER,...etc) and saves them in an optimization matrix. This matrix is input to the deep learner tool to undergo an optimization algorithm. The result of this algorithm is saved into a matrix and is overwritten in the storage unit for further use.

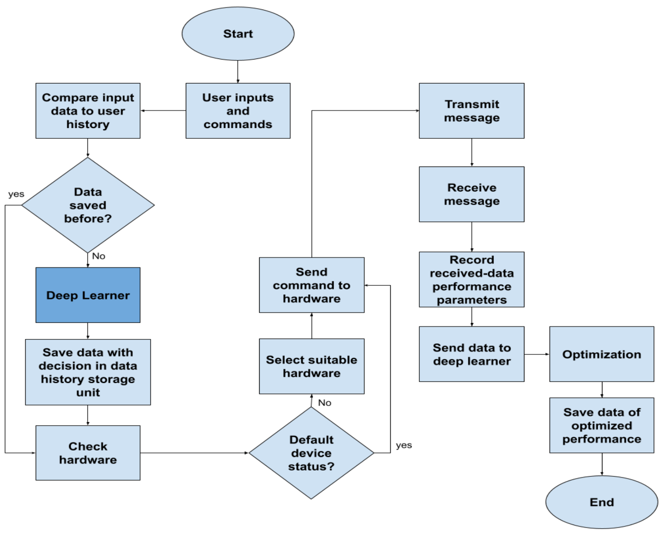

Fig. 2. The flowchart for the process of the proposed system.

C. Deep Reinforcement Learning Tool

Deep learning is a powerful tool for developing data processing algorithms for various engineering designs challenges [7]. Deep neural networks can learn the complicated features in nature-made signals, which are the uncontrollable meteorological changes experienced by the propagating signal in our case, and use them for classification and decision making. Although there are known algorithms for channel modeling in the literature, the experiment proves many problems accompanied by using a known algorithm for reaching an optimal model [7]. First, the use of a fixed, known algorithm has prohibitively high complexity for real-time implementation. Second, the use of standard system models is inadequate or incomplete [3]–[5] and [7]. The reason for choosing DL in our system is that our objective is achieving performance enhancement depending on large number of layers, and we choose the reinforcement type in particular because we are dealing with natural parameters which are related to the channel. It is hard to give an efficient decision when using either supervised or non-supervised learning when dealing with a time-variant parameters, especially when dealing with the atmospheric channel. One of the input vectors to the DL tool is a real-time measurement of the atmospheric parameters: temperature, relative humidity, air pressure, etc. These parameters are sufficient to determine the actual status and the real-time attenuation coefficient and scintillation index of the channel. Another main input vector to the DL tool is a real-time status check for the connected devices. This vector only consists of binary values: '1' in case of faulty device and '0' in case of working device.

In [7], it is proved that deep learning tool has two efficient applications in communications engineering. The first application is that it can output an approximation for a complicated computationally algorithm with no need to use iterating the algorithm for a large number. Such iterative algorithms are neither practical nor useful in optical communication systems where latency constraints require execution times below nanoseconds or even picoseconds in the case of optical communications. The second application presented in [6] is that deep learning inverts an unknown function. Non-linear distortion can occur between the transmitter and receiver, which results in an increase of loss up to 120 dBm/km in the case of using MIMO systems [1], [5].

III. Performance Evaluation of Proposed System

We study the performance of the proposed system through three main parts: the resulting SNR and BER, the behavior of the system when the transmitter and the receiver are misaligned which leads to pointing error occurrence, and the life-span of the used optical devices due to consumption.

A. SNR and BER

The type of photodetector used in the optical receiver unit affects the resulting BER and SNR. The SNR is the ratio of the transmitted signal's power to the noise's power experienced by the traversing signal. This noise power is due to the atmospheric channel besides the thermal noise in the devices while processing. Shot and intensity noises are generated due to laser sources and photodetector operations. Multiplication noise is only considered in the case of using avalanche photodetector. The BER is the number of bits transferred incorrectly per unit time or per the total number of bits transferred. As the SNR increases, the BER decreases. The most BER accepted for a reliable communication link is 10^{-3}.

B. Pointing Error Due to Geometrical Loss

The pointing error results from transmitter-receiver misalignment due to beam divergence, temperature, and window loss resulting from the collimator lens. The geometrical loss due to beam divergence, L_G, for Gaussian beam is given by [1], [3], [4]

$$L_G = 10\log\left[1-\exp\left(-2\left(\frac{D}{L\tan\left(\frac{\theta_{\mathrm{div}}}{2}\right)}\right)^2\right)\right]. \quad (4)$$

where, D is the diameter of the collimator lens and θ_{div} is the divergence angle of the laser beam. The geometrical loss can be reduced by using larger aperture diameters at the receiver. However, this is achieved with a tradeoff of experiencing windowless due to the collimator thickness and material. In [3], the wind speed for predicting the average pointing loss is found to be 6.7 dB. From the obtained measured values of wind speed for Alexandria City, Egypt climate represented in [4] we find that L_G depends on wind speed.

C. Life-span of Optical Communication Devices

In [8], it is shown that the typical life-time of optical communication devices ranges from 10,000 to 100,000 hours. However, if the optical devices continue operating at a rising temperature in a hot climate degrades the devices' efficiency, and the life span can drop to the range of 1000-5000 hours [4], [8]. Therefore, some data sheets in [8] recommend operating the laser diode at 70-80% of the rating power resulting in a significant increase in the life-time. This is not efficient when dealing with high capacity communications, especially when operating within security companies located in rural desertous areas, which need to work at full capacity for more than 24 hours. The data for the commonly used optical communications devices are saved in the VHDL memory as given data for the deep learner to give the right operating decision.

IV. Results and Discussion

In this section, we discuss our results for the proposed system. The discussion is divided into three parts: system performance results, life span of optical devices consumption, and system execution time. We studied the system performance in different conditions of attenuation and atmospheric turbulence (weak, moderate, strong). Since our main objective is to discuss the system performance in the worst case (strong turbulence), we concentrate our discussion for the results obtained by using the parameters shown in Table 1.

TABLE I
Operating Parameters of the Proposed FSO System in case of Strong Atmospheric Turbulence.

Operating parameter	Value
Transmitter power per laser source (P_t)	3 mW
Laser beam divergence angle per laser source (θ_{div})	1 mrad
Transmitter efficiency (τ_{trans})	0.8
Receiver efficiency (τ_{rec})	0.75
Wavelength (λ)	1550 nm
Link length (L)	1 km
Receiver sensitivity (N_b)	-30 dBm
Data rate (R) in SISO configuration	155 Mbps
Data rate (R) in MISO, SIMO and MIMO configurations	2.5 Gbps
Dark current (I_D)	10 nA
Collimator lens diameter at receiver (D)	5 cm
Electrical bandwidth (B)	0.5 GHz
Effective number of large scale eddies (α)	10
Effective number of small scale eddies (β)	1.4

A. System Performance Results

This subsection discusses the system performance through the resulting BER and SNR. We present the performance results for SISO, MISO, SIMO, and MIMO system configurations. The results are shown in Figures 3, 4, 5 and 6, respectively.

In Figure 3, the performance of our proposed system is compared to the system model presented in [4], which interprets SISO configuration and considers the case of atmospheric absorption effect only. Our contribution in this part compared to the system model in [4] is that we consider the effect of strong atmospheric turbulence with atmospheric absorption effect. In case of using non-return-to-zero on-off-keying (NRZ-OOK) modulation, we find that our proposed system enhances the performance by approximately 18% compared to the system in [4]. However, our proposed system shows an approximate enhancement by 12% in case of using 16-QAM-OFDM modulation. The main reason for this limited enhancement is the strong atmospheric turbulence.

In Figure 4, the performance of our proposed system is compared to the system model presented in [9], which interprets MISO configuration. In case of interpreting MISO4X1, the proposed system enhances the system performance by nearly 13%. However, in case of MISO8X1, the proposed system shows an enhancement by 22% and an enhancement by nearly 20% in case of MISO16X1 configuration. We notice that although our proposed system shows a better BER-SNR behavior by an average 19% in case of MISO configuration compared to the model in [9], the effect of diversities are almost diminished in case of strong turbulence.

In Figure 5, the performance of our proposed system is compared to the system model presented in [10], which interprets SIMO configuration and considers perfect LoS connection (no pointing error). Our contribution in this part compared to the system model in [10] is that we consider the effect of transmitter-receiver misalignment. In case of interpreting SIMO1X4, the proposed system enhances the system performance by nearly 26%. However, in case of SIMO1X8, the proposed system shows an enhancement by 25% and an enhancement by nearly 24% in case of SIMO1X16 configuration. We notice that although our proposed system shows a better BER-SNR behavior by an average 25% in case of SIMO configuration compared to the model in [10], the effect of diversities are almost diminished in case of strong turbulence.

In Figure 6, the performance of our proposed system is compared to the system model presented in [5], which interprets MIMO configuration and considers perfect LoS connection (no pointing error). Our contribution in this part compared to the system model in [5] is that we consider the effect of transmitter-receiver misalignment. In case of interpreting MIMO4X8, the proposed system enhances the system performance by nearly 24%. However, in case of MIMO16X16, the proposed system shows an enhancement by 12%. We notice that although our proposed system shows a better BER-SNR behavior by an average 18% in case of MIMO configuration compared to the model in [5], the effect of diversities are almost diminished in case of strong turbulence.

B. Life-span of Optical Devices Consumption

The bar chart in Figure 7 shows the resulting average life-span of optical devices (in hrs) in cases of using a conventional system and using our proposed system. Since the chart considers the average life-time of used devices at different MISO and MIMO configurations, we find that the maximum consumption hours at some configurations (e.g., in MISO2X1, MISO4X1, MIMO2X2) is too small compared to

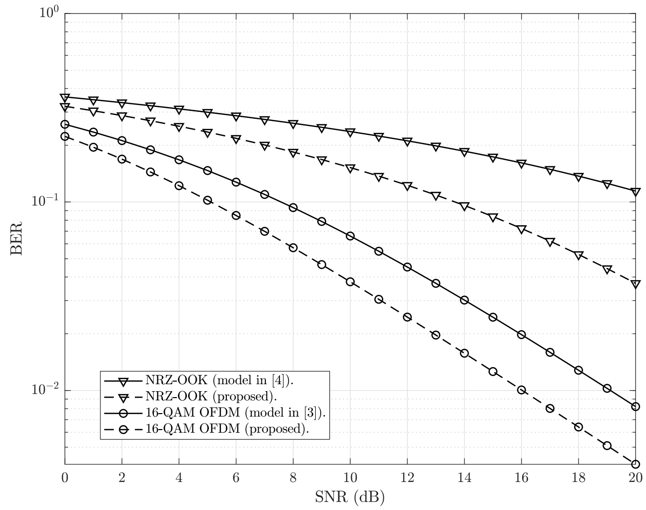

Fig. 3. BER performance of SISO system for the proposed model compared to the model in [4].

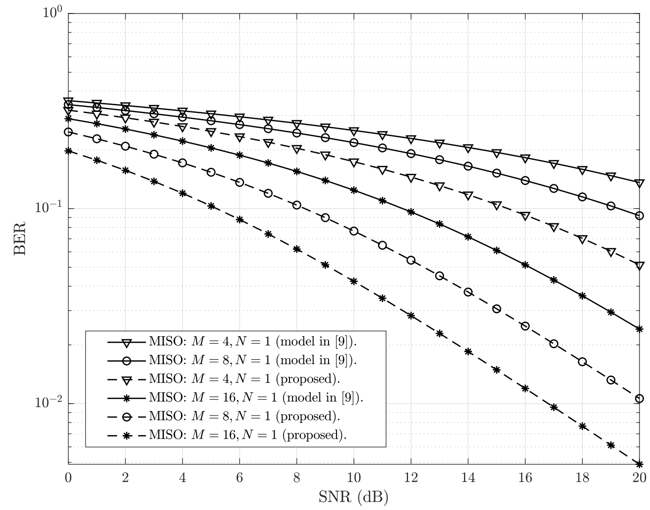

Fig. 4. BER performance of different configurations of MISO systems for the proposed model compared to the conventional model used in [9].

other configurations. Using a conventional MISO or MIMO configuration under the given channel conditions results in a devices' life-span range of 1000-20,100 hrs. The reason for such a significant drop in the life-span given in [8] is due to the presence of high temperature and humidity in our channel [4], which also affects the performance of the device due to ambient and thermal noises [4]. However, our system results in a significant increase in the device life-span by a range of 95-98% compared to the case of using the conventional configuration and by 84-88% compared to the expected life-spans given in [8].

C. System Execution Time

The bar chart in Figure 8 compares the system execution time when using a conventional configuration and when applying our system configuration. The conventional configuration shows an execution delay of 0.0550-1.26 seconds. This delay is too critical in the case of dealing with high-priority data at high data rates, which can cause a bottleneck at the receiver. However, our system shows an execution range of 100 ns - 600 μ sec. Our system shows an approximate 98-99.98% time saving compared to the time delay resulting from a conventional processing system.

V. Conclusions and Future Work

In conclusion, there is an annual savings of nearly 25% of cash flow for system devices consumption in case of operating in high-temperature rural areas (e.g., Borg Al-Arab, Alexandria city, Egypt as considered in [4]). The results show an 83.34% system efficiency enhancement when using the second model in moderate atmospheric turbulence (using gamma-gamma model). However, in case of severe atmospheric turbulence, we find that the diversity effect diminishes when using MISO, SIMO, and MIMO diversities. In case of using SISO configuration, the proposed system enhances the performance by 18% and 12% for OOK-NRZ and 16-QAM-OFDM, respectively, compared to the model in [4]. In case of using MISO configuration, the proposed system enhances the performance by 19% compared to [9].In case of using SIMO configuration, the proposed system enhances the performance by 25% compared to the model in [10].In case of using MIMO configuration, the proposed system enhances the performance by 18% compared to the model in [5].The system shows an overall average enhancement by 24% in case of severe atmospheric turbulence. This proposed hybrid model is proved to be applicable to any atmospheric channel conditions. There was a significant increase in the device life-span by a range of 95-98% compared to the case of using the conventional configuration and by 84-88% compared to the commonly

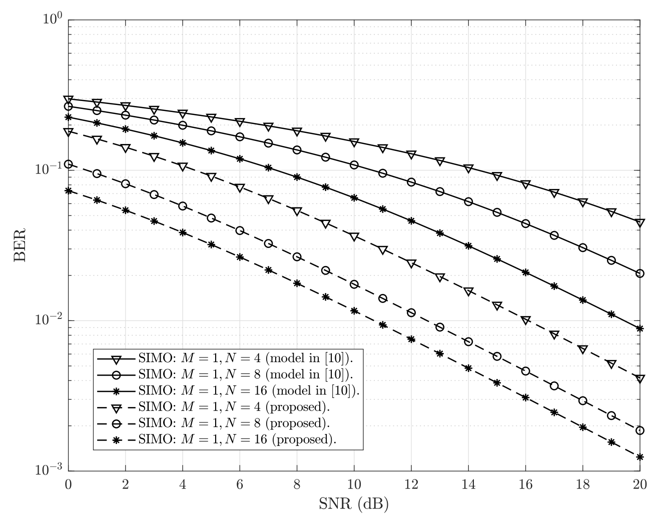

Fig. 5. BER performance of different configurations of SIMO systems for the proposed model compared to the model in [10].

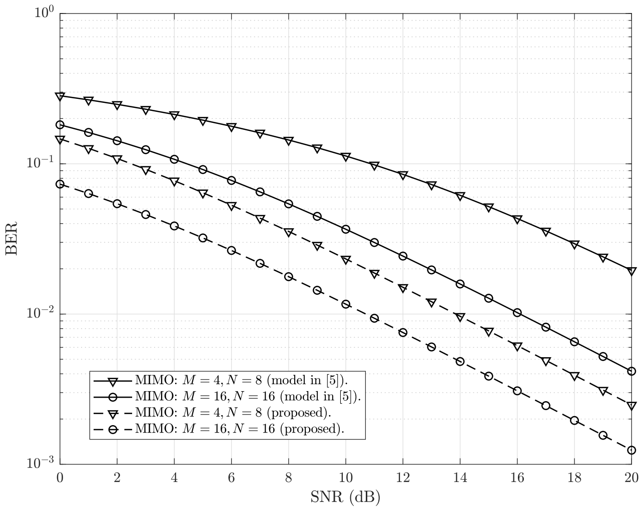

Fig. 6. BER performance of different configurations of MIMO systems for the proposed model compared to the model in [5].

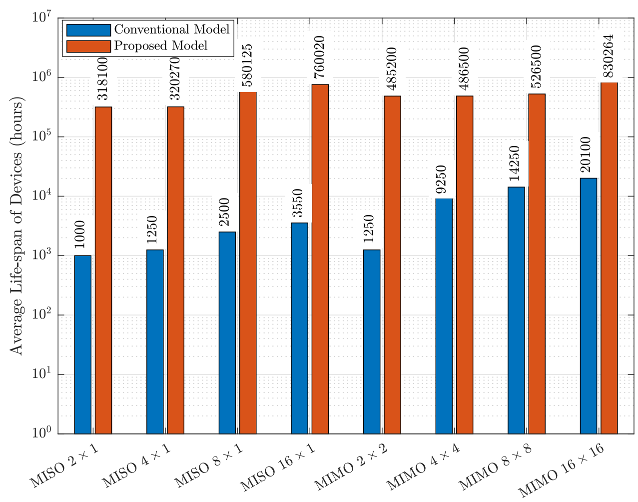

Fig. 7. Expected Average Life-time of Optical Devices In Cases of Using Conventional Systems (blue bars) and Using Our System (Red Bars).

expected life-spans. A range of 98-99.98% execution time saving is achieved compared to conventional systems. This efficient time saving is critical for security applications and communications demands required in rural areas. One trade-off is that the difference in the performance between our system and the conventional ones at using MIMO 2×2, MISO 2×1, MISO 4×1 is not significant. However, the efficient use of devices in our system allows extending the device's life-span.

We are currently working on implementing this system experimentally using VHDL. We expect to find that thermal effect of devices while operation will dramatically affect the system performance, especially when dealing with high data rates. We are studying the system performance and we will compare it with the simulation results obtained in this paper.

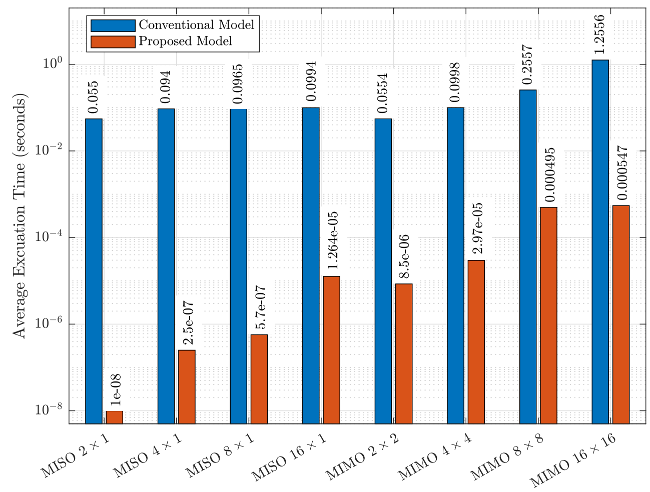

Fig. 8. Comparison between conventional systems and the proposed systems in terms of system execution time.

According to the comparison results, we shall enhance our system design later on.

References

[1] H. Huang, J. Chen, H. Chen, Y. Huang, Y. Li, Y. Song, N. K. Fontaine, R. Ryf, and M. Wang, "Secure free-space optical communication via amplified spontaneous emission (ASE)," in Proc. *Opt. Fiber Commun. Conf. (OFC 2020),* San Diego, CA, USA, 8-12 Mar. 2020, pp.1-–3.

[2] M. Jin et al., "Hybrid dual-hop RF/FSO terrestrial-deep space communication system under solar scintillation during superior solar conjunction," *Applied Sciences,* vol 12, no 2, 2022.

[3] J. Poliak, P. Pezzeiy, E. Leitgehy, and O. Willfort, "Analytical expression of FSO link misalignments considering Gaussian beam," in Proc. *18th Eur. Conf. Netw. Opt. Commun. 8th Conf. Opt. Cabling Infrastructure (NOC-OCI2013),* Graz, Austria, 10-12 Jul. 2013, pp. 99–104.

[4] A. A. Algamal, H. A. Fayed, M. M. Aly, and M. H. Ali, "Reliable FSO system performance matching multi-level customer needs in Alexandria city, Egypt, climate: Sandstorm impact with pointing error," *Opt Quant Electron,* vol. 52, article no. 349, Jul. 2020.

[5] W. O. Popoola, "Subcarrier intensity modulated free-space optical communication systems," Ph.D. dissertation, School of Computing, Engineering and Information Sciences, University of North Umbria at Newcastle, Sep. 2009.

[6] W. G. Sullivan, E. M. Wicks, C. P. Koelling, *Engineering Economy,* Seventeenth Edition, New Jersey, Pearson, 2017.

[7] E. Bjornson and P. Giselsson, "Two applications of deep learning in the physical layer of communication systems [Lecture Notes]," *IEEE Signal Process. Mag.,* vol. 37, no. 5, pp. 134–140, Sept. 2020.

[8] Alldatasheet.com, "BPW34 Datasheet, PDF," Alldatasheet. [Online]. Available: https://www.alldatasheet.com/[Accessed: 13-Nov-2021].

[9] R. Boluda-Ruiz, S. C. Tokgoz, A. García-Zambrana, en K. A. Qaraqe, "Enhancing secrecy capacity in FSO links via MISO systems through turbulence-induced fading channels with misalignment errors," *IEEE Photonics J.,* vol 12, no. 4, pp. 1-–13, Aug. 2020.

[10] N. A. Androutsos et al., "Block error performance of PAM or PPM SIMO FSO links over strong turbulence channels," in Proc. *10th Int. Conf. Modern Circuits Sys. Technol., (MOCAST 2021),* Thessaloniki, Greece, 5-7 Jul. 2021, pp. 1–4.